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THE DISTRIBUTION OF FRACTURE TOUGHNESS: DATA FOR D6AC STEEL,(U)
AUG 76 J COYLE, J M GRANDAGE, D G FORD
UNCLASSIFIED ARL/STRUC NOTE-429 NL

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THE DISTRIBUTION OF FRACTURE TOUGHNESS DATA FOR D6ac STEEL

by

JACQUELINE COYLE, J. M. GRANDAGE and D. G. FORD

AUGUST 1976

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DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANIZATION

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STRUCTURES NOTE 429

THE DISTRIBUTION OF FRACTURE TOUGHNESS: DATA FOR D6ac STEEL

by

JACQUELINE COYLE, J. M. GRANDAGE and D. G. FORD

SUMMARY

Data on fracture toughness for D6ac steel is analysed for conformity with three probability distributions. The three parameter extreme value distribution is selected, and parameters are estimated for specified conditions.

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CONTENTS

1. INTRODUCTION

A.R.L. have recently applied reliability theory to structural fatigue, allowing estimation of safe inspection intervals in service (~~Refs. 1 and 2~~). The method recognises various inputs which influence the risk of failure. One input is the distribution of residual strength of structures all cracked to the same extent. This is important in view of the high variability in fracture toughness for some materials, and the corresponding variability in residual strength for a given crack size.

The feasibility of applying the method was investigated using the example of an aircraft having many components made from D6ac steel heat treated to strength levels of 220–240 k.s.i. Five locations in D6ac components were considered possible sites for fatigue failures. Much fracture toughness data for D6ac steel was available. This was analysed to identify its distribution, and to estimate its parameters at each failure site.

This report presents this analysis.

2. GENERAL REQUIREMENTS

The requirement is to identify and estimate parameters of fracture toughness distributions for the five failure sites at temperatures which are appropriate for two types of condition. These conditions are firstly flight operating conditions, and secondly low temperatures corresponding to a cold proof load test, to which the aircraft is subjected before entering service. These temperatures are specified in detail in section 4.

It should be noted that although all the failure sites are in D6ac components, they were not all heat treated by the same process, and thus mean fracture toughness *at the same temperature* could be expected to vary among the failure sites.

3. DATA

Samples of fracture toughness data are given in Refs. 3 and 4. Ref. 3 gives extensive data obtained during a multi-laboratory test programme in the U.S. Ref. 4 gives a smaller quantity of data from D6ac components from the aircraft.

The data from Ref. 3 covered a wide range of testing parameters, and the following parameters were shown to have an important effect on the mean and/or variability of fracture toughness K_{Ic}:

(*a*) Testing Temperature.

(*b*) Local quench rate, which is determined by the heat treatment process and also by parameter (*c*).

(*c*) Thickness of material during heat treatment. (As well as being variable itself the thickness during heat treatment often differed from the thickness of the specimen tested).

(*d*) Type of specimen. Three types were used; compact tension, surface flaw and double cantilever beam.

(*e*) Material batch number.

(*f*) Position of specimen within the part.

Ref. 5 gives estimates of mean K_{Ic} values for each failure site, and also the variation of K_{Ic} with temperature.

4. ANALYSIS PROCEDURE

The analysis consisted of two stages. Firstly it was assumed that a common form of distribution for K_{Ic} of D6ac steel exists under all testing conditions, and this form was estimated by means of standardising and pooling data from different samples to give the largest possible pooled data sample. Secondly the parameters of the distributions were estimated by considering data relevant to each failure site at appropriate temperatures.

4.1 Form of Distribution

Refs. 3 and 4 contain a small proportion of data stated to be invalid, and these are excluded from the present analysis. The valid data were grouped into 10 samples, each having a characteristic testing temperature, heat treatment and specimen type. This grouping gave samples which included variability associated with batch number, geometric variations and inherent variability caused by micro defects. A total of 406 data points were obtained. The details of the samples are listed in Table I. It is noted that data at $-40°F$ and $-65°F$ are combined into the same sample. This was desirable because of the small sample sizes at each temperature alone, and was considered justified by the small differences in data between the two temperatures.

For pooling purposes the data were standardised as

$$x = (K - \bar{K})/S$$

where $\bar{K}$, S represent various means and standard deviations for the relevant subsamples. A similar variate based on log K was used to compare with the log normal distribution. The standardised data were then pooled into a common ordering system. The empirical distribution of the data was plotted on normal probability paper (Figs. 1, 2) to compare it with the normal distribution. It should be noted that in Figures 1 and 2 every point has been plotted at probabilities greater than 90% and less than 10%, whereas between these values every tenth point has been plotted. An inspection of the common ordering system showed that there was no strong tendency towards clustering of data from any particular sample. This supports the initial assumption that a common distribution form exists for all samples, and that data from various samples can be pooled after standardising. Figs 1 and 2 indicate that the Normal and log Normal distributions are fairly good fits to the data.

The data from group 5 (Table I), consisting of the largest sample of 154 data points, was then compared with the two parameter extreme value distribution, defined as

$$P(K) = 1 - \exp\{-(K/\upsilon)^{\alpha}\}$$

where

K = fracture toughness K_{I_c},
$P(K)$ = probability that K is less than the nominated value,
υ = characteristic value of K, for which $P(K) = 0{\cdot}63$,
α = dispersion and shape parameter.

This sample alone was used because there was no readily available method of standardising the data from different samples which is compatible with the extreme value distribution. In this instance the use of one sample alone is justified by its large size, and also by the point made in the previous paragraph that there was no strong tendency for any sample to appear clustered in the total pool of data. Fig. 3 compares the data with the two parameter extreme value distribution, and clearly the fit.

As an alternative the three parameter extreme value distribution was investigated. This is defined as

$$P(K) = 1 - \exp\left\{-\left(\frac{K - \varepsilon}{\upsilon - \varepsilon}\right)^{\alpha}\right\},$$

where

ε = least value of K, for which $P(K) = 0$, and υ, α are as before.

The result is shown in Fig. 4. Clearly this is an improvement on the two parameter distribution.

Comparing Figs 1, 2 and 4 suggests that the Normal, log Normal and three parameter extreme value distributions all give a fairly reasonable fit to the data. The Kolmogarov-Smirnoff test (Ref. 6), a non-parametric test which makes no specific assumptions about the form or parameters of the distribution being tested, also indicated that both distributions fitted the data adequately. The tests were significant at approximately 10%, 15% and 20% respectively for the Normal, log-Normal and the three-parameter extreme value distributions. Thus it cannot be concluded statistically which of these three is preferable.

The extreme value distribution was selected because it allows the choice of a least possible value of K_{I_c}: the normal distribution predicts a finite probability of achieving a very low (or even negative) value of K_{I_c}. In practice it is reasonable to expect a non-zero least value to be imposed by manufacturing quality control.

4.2 Parameters of Distributions

Estimates of the parameters υ, ϵ and α are required for conditions of heat treatment temperature and specimen type which are appropriate for the five failure sites. As regards specimen type, the data in Ref. 3 suggests that the surface flaw type gave higher values of fracture toughness than the other specimen types. For this reason surface flaw specimen data were not considered when estimating parameters of distributions. The heat treatment processes for the various failure sites were known in terms of the processes used for the data in Refs. 3 and 4. As discussed above in section 2, temperatures were required to be appropriate for cold proof load test conditions as well as for normal operating conditions. It was anticipated that the proof load test could be applied at either −40°F or −65°F, and both these temperatures were considered. Operating temperatures could typically vary from 0°F to 75°F, with short periods of high speed flight at higher temperatures. In view of the reduction in K_{Ic} at low temperatures, it was decided to consider operating temperatures of 0°F and 20°F as well as 75°F. To estimate the distribution parameters, appropriate samples from Refs. 3 and 4 were used, together with data from Ref. 5 giving mean K_{Ic} for each failure site and the variation of K_{Ic} with temperature. It is noted that the mean values in Ref. 5 in most cases differed from the corresponding sample means from Refs. 3 and 4 because of variations in local quench rate within the part, which are to some extent deterministic.

The procedure was to select data samples from Refs. 3 and 4 having the temperatures (nearest to the required temperatures), heat treatment and specimen type for each failure site. In many cases these distributions were shifted to give the appropriate mean values from Ref. 5, making due allowance for temperature variations (also from Ref. 5), without altering the shape of the distributions. In carrying out this mean shift it was assumed that either the standard deviation or the coefficient of variation remained constant. Coefficient of variation was held constant if the mean shift was required to account for within the part variations of K_{Ic} at the same temperature, and standard deviation was held constant for mean shift due to temperature. This was because, for the data in Ref. 3, the mean and standard deviation were both reduced by lowering temperature, whereas the standard deviation did not appear to vary systematically with sample mean at the same temperature. Finally the extreme value parameters were estimated graphically using extreme value probability paper and the expressions in Ref. 7 for relation ships between the various parameters. The results are shown in Table II.

5. CONCLUSIONS

1. The analysis suggests that a common distribution form exists for the fracture toughness data considered, although the parameters vary greatly according to the testing conditions.

2. The data is fitted adequately by Normal, log-Normal and three-parameter extreme value distributions. This generally agrees with the conclusions of reference 8 for airframe materials.

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TABLE I
Description of K_{Ic} Data Samples

(1) Sample Number	(2) Specimen Type	(3) Heat Treatment	(4) Temp. (°F)	(5) Sample Size	(6) Source of Data	(7) Sample Mean	(8) Sample S.D.
1	CT	E	−40 & −65	16	Ref. 3	36·7	3·47
2	CT	A	70	51	Ref. 3	95·8	4·93
3	CT	B	70	13	Ref. 3	85·6	9·89
4	CT	B	−40 & −65	13	Ref. 3	45·6	3·34
5	CT	E	70	154	Ref. 3	64·7	11·20
6	DCB	E	70	21	Ref. 3	65·9	11·00
7	CT	H	70	33	Ref. 3	56·5	13·64
8	SF	E	70	57	Ref. 3	81·2	18·50
9	SF	E	Unknown	20	Ref. 3	78·7	15·36
10	CT	E	70	28	Ref. 4	52·1	5·65

(2) — Compact Tension, Double Cantilever Beam, or Surface Flaw.
(3) — "A" and "B" — High Toughness Process
"E" — Medium Toughness process
"H" — Low Toughness Process
(4) — Data at −40°F and −65°F was combined.

TABLE II

Parameters of K_{Ic} Distributions

For each failure site and temperature, Table gives:

Mean	S.D.
υ	ε
k	ε/υ

Failure Site	Heat Treatment	TEMPERATURE (°F)									
		75		20		0		−40		−65	
1	A	85	4·93	71	4·12	65·5	3·80	53	3·69	46·5	3·69
		87·5	65·6	73·1	54·8	67·4	50·5	54·3	40·7	48·0	36·0
		21·7	0·75	21·7	0·75	21·7	0·75	17·9	0·75	15·6	0·75
2	A	85	4·93	71	4·12	65·5	3·80	53	3·69	46·5	3·69
		87·5	65·6	73·1	54·8	67·4	5·05	54·3	40·7	48·0	36·0
		21·7	0·75	21·7	0·75	21·7	0·75	17·9	0·75	15·6	0·75
3	E	75	11·20	60·5	9·03	55·5	8·29	46·5	2·26	41·5	2·26
		79·0	53·7	63·5	43·2	58·3	39·7	47·8	40·1	42·6	35·8
		8·00	0·68	8·00	0·68	8·00	0·68	26·3	0·84	23·2	0·84
4	E	55	11·20	43·5	8·86	40·5	8·25	35·5	2·26	34	2·26
		58·5	37·4	46·0	29·4	43·0	27·5	36·5	29·2	34·9	27·9
		5·71	0·64	5·71	0·64	5·71	0·64	19·6	0·80	18·5	0·80
5	E	65	11·20	51·5	8·87	47·5	8·12	40·5	2·26	37·5	2·26
		68·0	44·2	54·5	35·4	50·0	32·5	41·6	34·1	38·5	31·6
		6·90	0·65	6·90	0·65	6·90	0·65	22·7	0·82	20·4	0·82

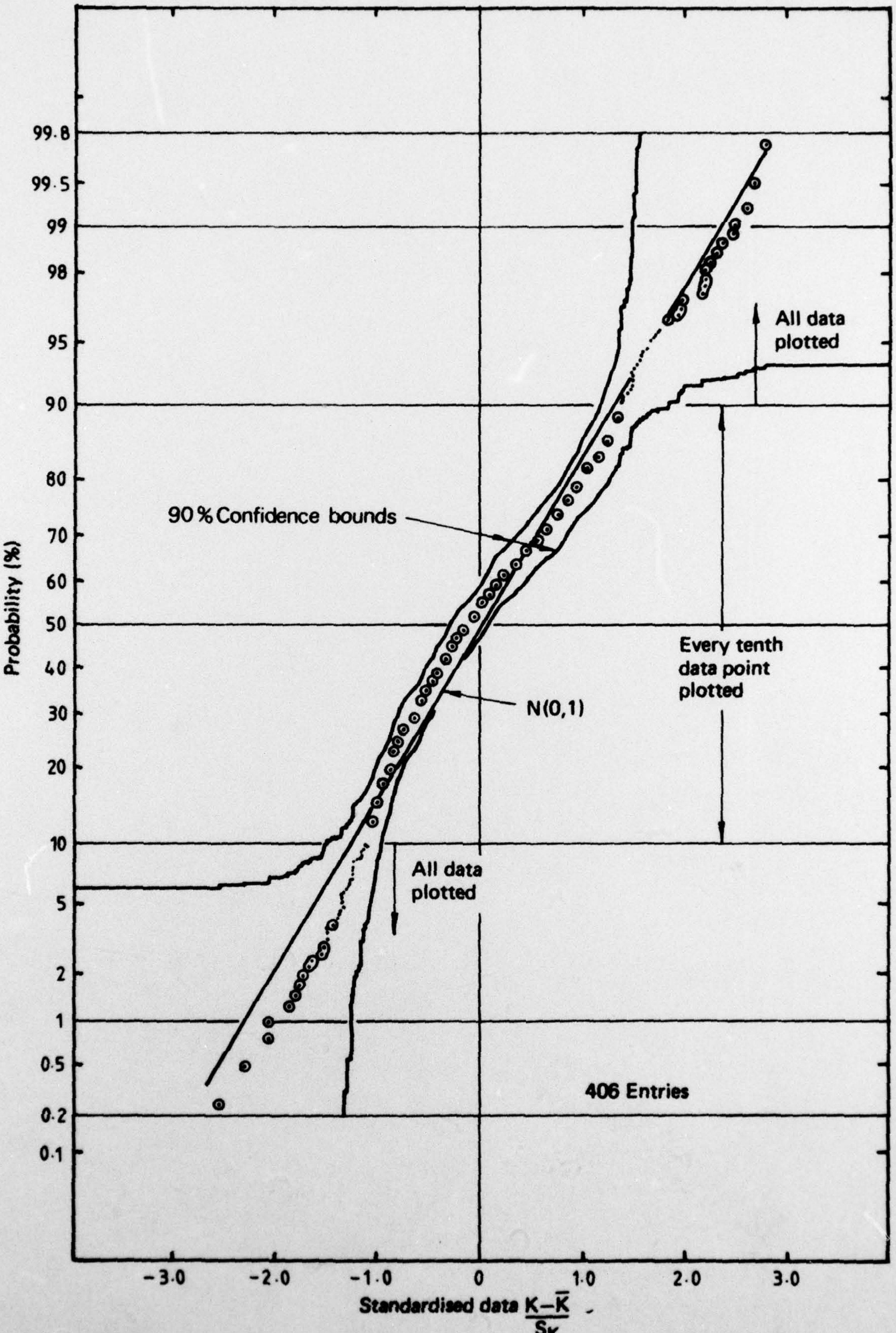

FIG.1 COMPARISON OF POOLED DATA WITH NORMAL DISTRIBUTION

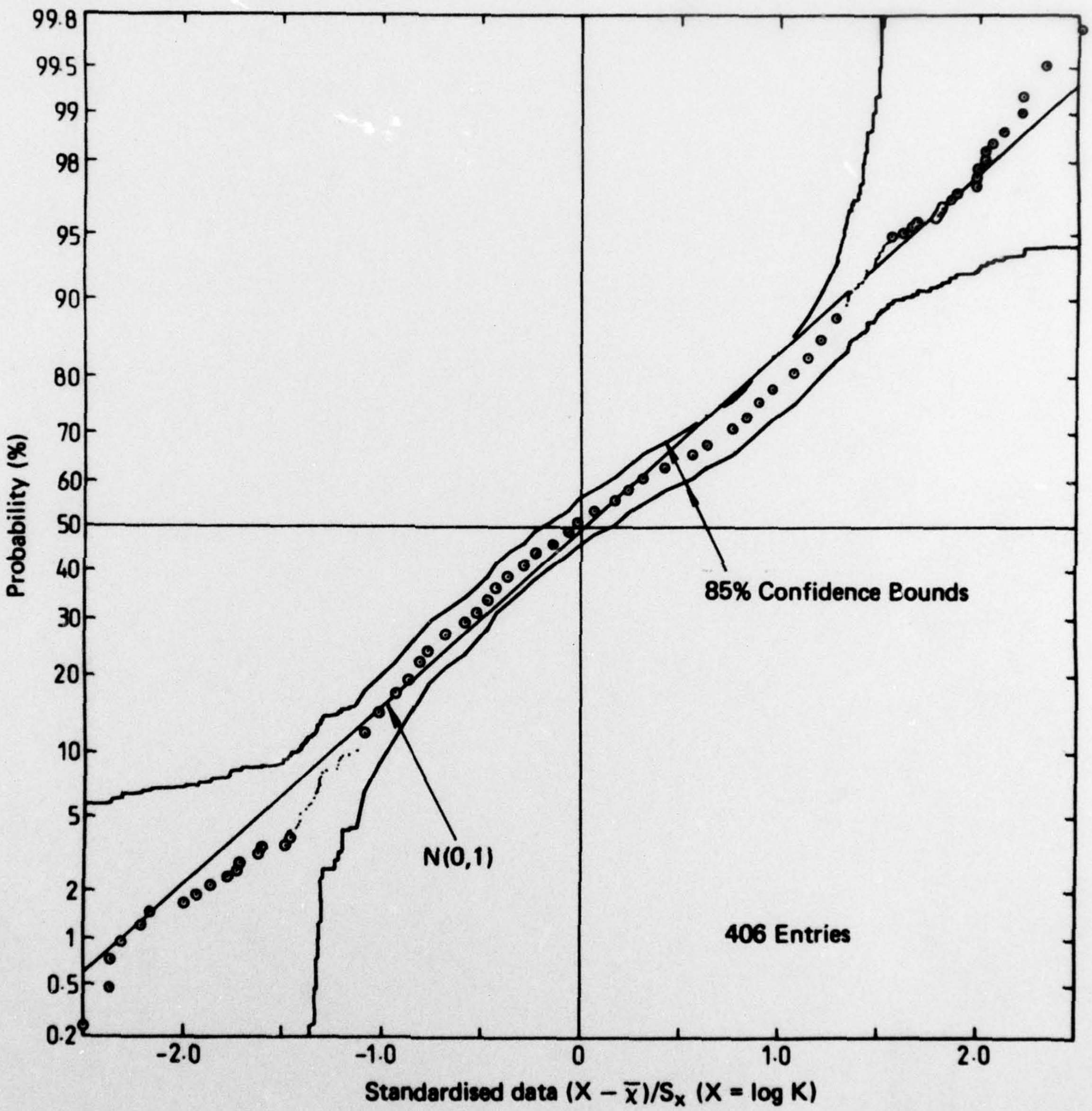

FIG. 2 COMPARISON OF POOLED DATA WITH LOG NORMAL DISTRIBUTION

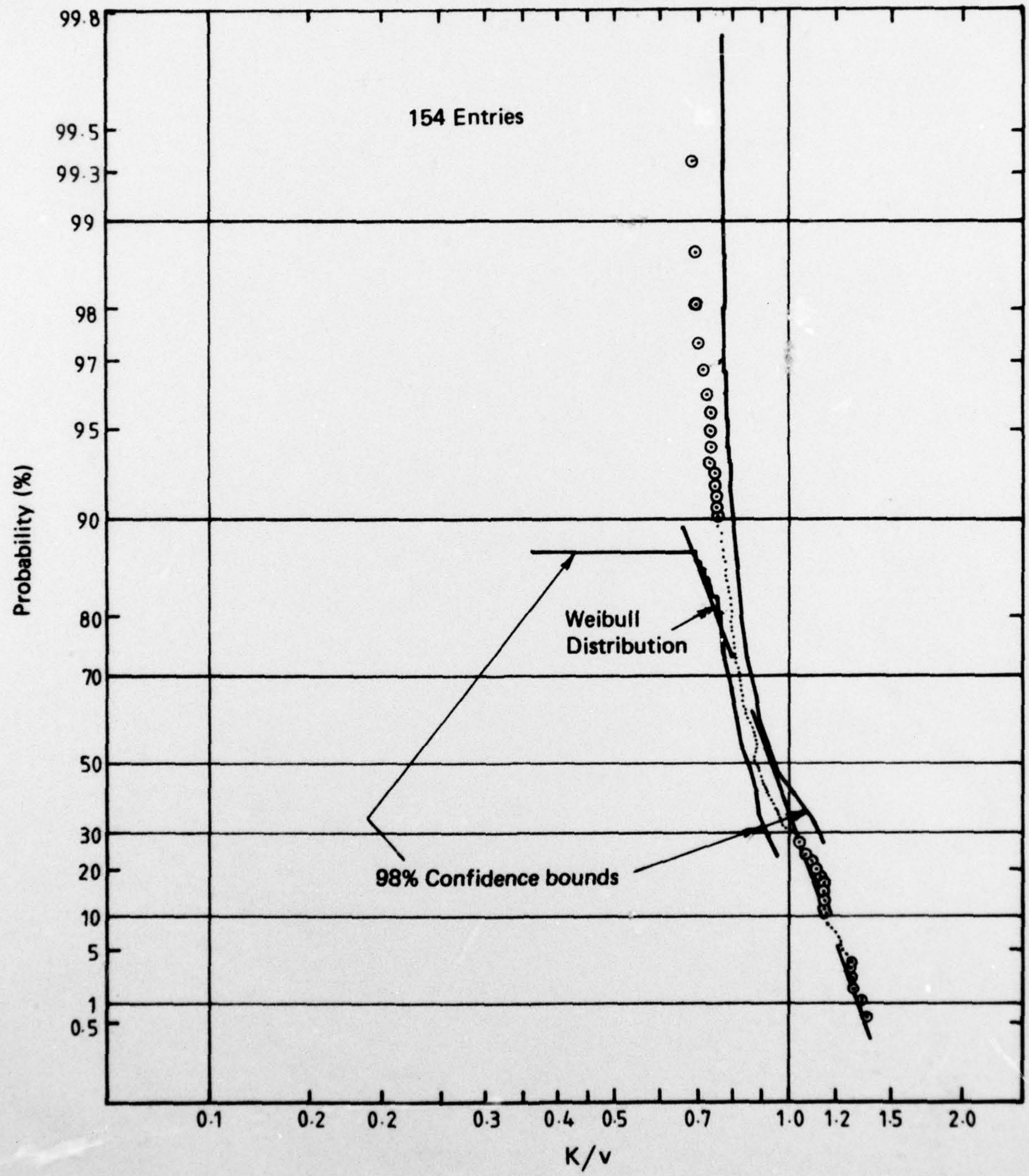

FIG. 3 COMPARISON OF DATA WITH TWO PARAMETER EXTREME VALUE DISTRIBUTION

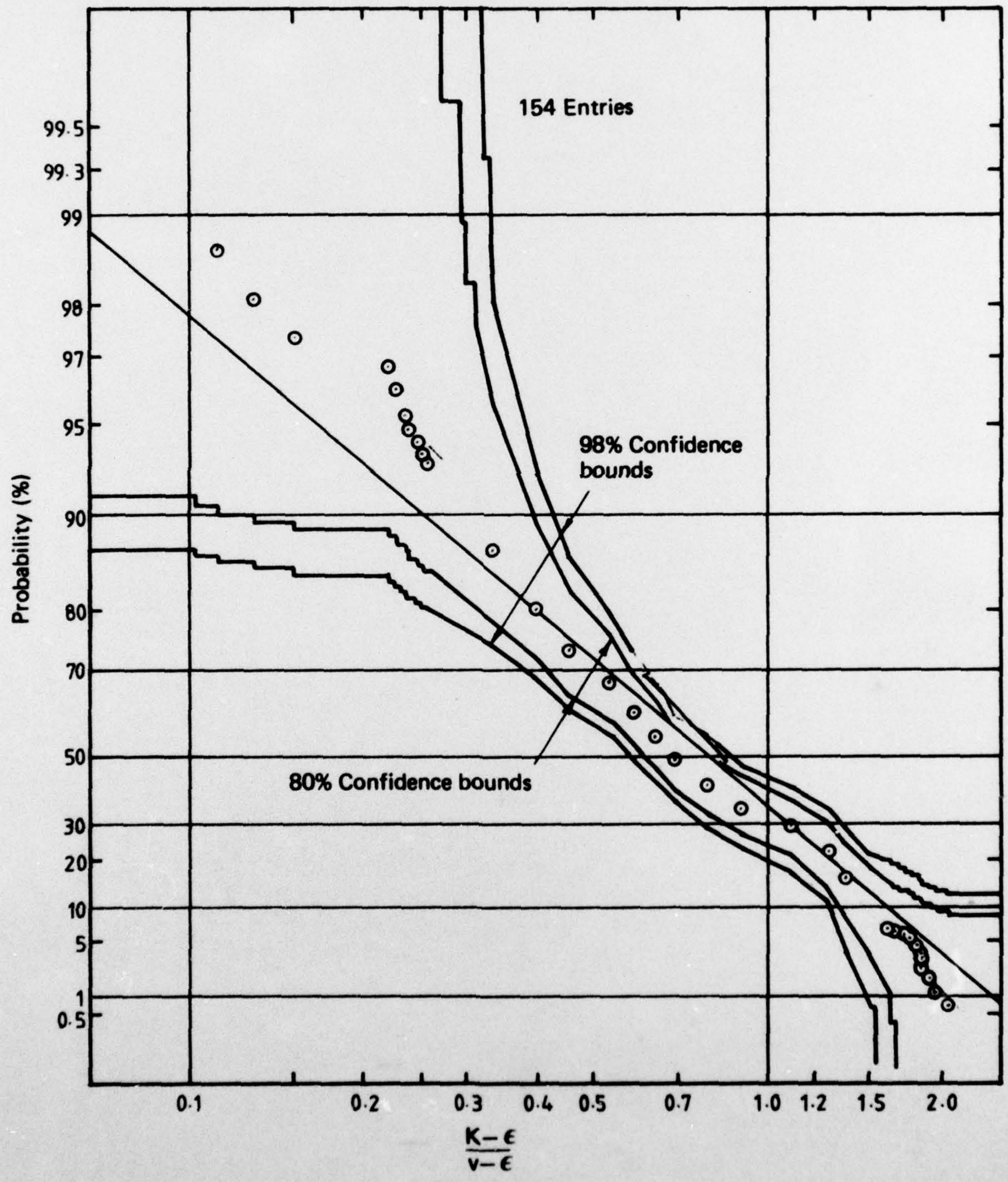

FIG. 4 COMPARISON OF DATA WITH THREE PARAMETER EXTREME VALUE DISTRIBUTION

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2. Document Type/Number
   Structures Note 429

3. Document Date
   11 Aug[redacted]76

4. Title and Sub-Title: 6 The Distribution of Fracture Toughness: Data for D6ac Steel

5. Personal Authors 10 Jacqueline Coyle, J. M. Grandage & D. G. Ford

6. Corporate Author(s) A.R.L. 14 ARL/STRUC NOTE-429

7. *Abstract*

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12 15 p.

8. Computer Program(s)—Titles and Language

ØØ8 65Ø

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   Toughness
   Statistical distribution
   High strength steel

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    R.A.N.R.L.
    S.T.I.B.
    J.I.O.

11. Cosati Classifications
    2012, 1201, 1106

12. Task Reference DSTP 10

13. Sponsoring Agency Reference
    DST 76/133

14. Cost Code
    277021

15. Imprint Melbourne—AERONAUTICAL RESEARCH LABORATORIES 1976

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DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

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Erratum

The last words of paragraph 3, page 2 "..... the fit." should be extended to read "... the fit is inadequate."